Matter, Atoms, and Quarks Notes

Understanding nuclear science topics requires understanding some nuclear science fundamentals. This presentation addresses the atom and its structure, states of matter, the Periodic Table of the Elements, and changes in matter.

Slide 3 – the atom graphic

- nucleus consisting of protons and neutrons; surrounded by electrons in discrete energy levels
- protons and neutrons made up of quarks (fundamental constituent of matter)
- mostly empty space

Slide 4 – atomic structure

- graphic illustrates relative sizes of constituents of an atom

Slide 6 – quark properties

- intrinsic properties of mass, electric charge, and spin
- note charges of Up and Down quarks (red circles)

Slide 7 – proton and neutron structure

- proton – 2 up quarks, 1 down quark creates positive charge of +1
- neutron – 1 up quark, 2 down quarks; charges cancel each other

Slide 8 – relative quark masses compared to proton and electron

Slide 11 – Periodic Table of the Elements

- all known chemical elements arranged in order of number of protons in atomic nucleus
- lanthanoid (lanthanide) and actinoid (actinide) series of elements shown as separate rows beneath table to minimize width of Periodic Table display
- note enlarged box for oxygen displaying arrangement of information for each element
- atomic weight (or mass) is sum of protons and neutrons in atomic nucleus
- elements of same color (Group) in graphic have similar chemical properties

Slide 13 – common isotopes of hydrogen

- protium – single proton in nucleus; 99.985% of natural hydrogen
- deuterium – proton + neutron in nucleus; 0.015% of natural hydrogen
- tritium – proton + 2 neutrons in nucleus; radioactive isotope with 12.3-year half-life

Slide 14 – common isotopes of carbon

- 98.9% of natural carbon is C-12

- 1.1% of natural carbon is C-13
- C-14 isotope is radioactive with 5700-year half-life

Slide 15 – arrangement of isotopes in Chart of Nuclides
- Z is number of protons (atomic number) in nucleus
- N is number of neutrons
- shaded isotopes stable; unshaded radioactive

Slide 17 – physical states of matter
- 4 states – solid, liquid, gas, plasma – determined by internal energy (temperature) of atoms

Slide 18 – physical changes in matter
- water good illustration – unique among substances in that solid state less dense than liquid state

Slide 19 – chemical changes in matter
- molecules formed by electron bonds between atoms
- chemical reactions involve breaking and making of electron bonds between atoms
- energy often liberated in chemical reactions
- graphic illustrates burning (oxidation) of methane

Slide 20 – nuclear changes in matter
- fission – splitting of heavy atom nucleus, liberating 2-3 neutrons and lots of energy
- fusion – combining of 2 very light nuclei into heavier nucleus, liberating lots of energy
- radioactive decay – process by which unstable nucleus becomes more stable by emitting energy in form of particles and ionizing electromagnetic waves

Slide 22 – fission illustrated
- fission energy constituents; fission fragments, liberated neutrons, radiation consisting of beta particles and gamma-rays

Slide 23 – fission fragment distribution
- bimodal distribution of fission fragments, with most probable fragments having atomic mass numbers of 95 and 137
- decay chains for fission fragments Sr-94 and Xe-140 illustrated (decay by beta particle emission)

Slide 24 – nuclear fission energy disposition – recoverable energy
- energy of fission fragments and delayed beta radiation deposited within fuel material as thermal energy
- fission neutron energy deposited within reactor cooling water as thermal energy
- gamma-ray energy deposited in various reactor materials as thermal energy

- >90% of nuclear energy converted to readily recoverable thermal energy

Slide 26 – fusion illustrated

- fusion reactions power sun and stars
- in terrestrial fusion, plasma of ionized gas formed from hydrogen isotopes (deuterium and tritium) under high temperature (100 million degrees Celsius) and pressure to produce high energy neutrons and helium nuclei
- fusion research taking place since 1950s
- many companies pursuing so-far elusive goal of producing heat and generating electricity from fusion
- two main approaches for trying to accomplish fusion
  - magnetic confinement uses very powerful magnets to confine superheated plasma where atoms fuse and produce energy
  - inertial confinement uses intense set of laser beams fired at target of atoms, compressing them to point of fusing
- after 70+ years of research, timeframe for achieving scientific breakthrough for fusion as net energy source remains unknown

Slide 27 – potentially useful fusion reactions

- nearly all stable isotopes lighter than iron and nickel will fuse with some other isotope and release energy
- deuterium and tritium most attractive isotopes for energy generation as they require lowest activation energy (thus lowest temperature), while producing most energy per unit weight
- table shows deuterium-tritium fusion has lowest threshold plasma temperature and highest maximum energy gain per fusion event; hence fuel focus for most fusion machine research
- note shorthand notation for different fusion reactions
  - D-^{3}He is fusion of deuterium and helium-3 nuclei
  - p-^{11}B is fusion of hydrogen (proton) and boron nuclei
  - D-T notation will hereafter be used for deuterium-tritium reaction

Slide 28 – fusion reaction rate vs plasma temperature graphic

- observe that D-T fusion has highest reaction rate at the lowest threshold ion (plasma) temperature of about 50 keV

Slide 29 – D-T fusion energy disposition

- ideally, He-4 nuclei (alpha particles) expend their energy in plasma, further heating it
- energy of 14.1 MeV neutrons normally captured in lithium blanket that produces more tritium and heat
- lithium blanket would be cooled by system’s primary coolant, which can then transfer heat (via heat exchanger) to working fluid of conventional power cycle to generate electricity

Slide 32 – types of radioactive decay

- in beta minus decay, neutron converts to proton when down quark changes into up quark
- in beta plus decay, proton converts to neutron when up quark changes into down quark
- electron capture considered type of beta decay because basic nuclear process, mediated by weak force, is same; i.e., proton up quark changes to down quark

Supplemental Slides

Slide 36 – fundamental forces of nature

- strong nuclear force – force that holds quarks together and binds protons and neutrons together in atomic nucleus
- electromagnetism – force that governs interaction of particles having electric charge
- weak nuclear force – force capable of transforming neutrons into protons and vice versa; cause of radiation phenomena such as beta, positron, and electron capture decay
- gravity – attractive force between bodies having mass; described by theory of general relativity

Slide 37 – electron configurations

- graphic illustrates how electron shells (energy levels) get filled
- atomic orbitals basic building blocks of atomic orbital model; each orbital can accommodate 2 electrons of opposite spin
- s subshell – single orbital (pale blue)
- p subshell – 3 orbitals (green)
- d subshell – 5 orbitals (pale brown)
- f subshell – 7 orbitals (purple)

Slide 38 – illustration of electron shell configurations

- He – 1s subshell filled
- Ne – 1s, 2s, and 2p subshells filled
- Ar – 1s, 2s, 2p, 3s, and 3p subshells filled
- Kr – 1s, 2s, 2p, 3s, 3p, 3d, 4s, and 4p subshells filled, etc.
- outer shell electrons involved in electron bonding

Slide 39 – electron shell diagram

Slide 40 – binding energy per nucleon graphic

- illustrates energy liberated in fission and fusion reactions
- binding energy – energy holding protons and neutrons together in atomic nucleus
  - maximum binding energy in “iron group” of isotopes
  - protons and neutrons less tightly bound in heavy isotopes and very light isotopes
- energy liberated when fission and fusion produce isotopes with higher binding energy per nucleon